CLIENT RELAY SIMULATION MODEL FOR CENTRALIZED WIRELESS NETWORKS

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Abstract

Client relay is a very promising concept for wireless data transmission networks. It is especially attractive for centralized networks, where the relaying process may be governed by the base station. However, currently there are no research results that estimate, whether client relay technology will actually be effective in a real network. As client relay systems demonstrate extremely complex interactions between network, data link and physical layers, the applicability of analytical modelling is very limited. Therefore, simulations tend to be the natural way of assessing the performance of relay networks. Unfortunately, currently there are no open-source system level simulators capable of addressing client relay performance in the realistic channel conditions. In order to tackle this problem, the model is being developed for detailed simulation of different media access and relay protocols in the real-world conditions. In this paper we discuss the system model used for simulations, implementation principles, simulation results and their relations with analytical results. The key features of our system are computational efficiency, flexibility, support for multiple arrival flows and channel models, as well as reliable measurement approaches, which guarantee non-shifted averages and establish distributions for obtained parameters.

Keywords: client relay, cooperation, wireless networks

Presenting Author's Biography

Alexander Pyattaev was born in St.-Petersburg, Russia, on March 16, 1988. He received the Bachelors degree in St.-Petersburg University of Telecommunications, St.-Petersburg, Russia. He is currently a Master's degree student in Tampere University of Technology, Tampere, Finland. He has publications on computer simulations in SUT and was employed as hardware designer in the area of network measurements. His current interests include wireless networking, peer-to-peer technologies, real-time digital signal processing and artificial intelligence.

1 Cooperative networking overview

Nowadays the ideas of cooperative networking and wireless relaying are very popular. A lot of research is done in the area, and the results are very promising.

Many studies are devoted to modelling physical channels when multiple users are accessing them [1], [2]. There are research initiatives concentrating on downlink traffic relaying and static relays [3]. Since the base station relay has been standardized by IEEE in 802.16j [4], their future seems to be quite bright.

The idea of using client stations as relays for uplink is neither standardised, nor widely implemented, although models for such case are already available as well. They typically concentrate on such topics as relaying protocols (decode and forward, amplify and forward and others) [5], rate control systems [6] or coding techniques. There are, of course, more generic studies concentrating on system level [7], as well as whole new network frameworks like WINNER [8], which support client relay by design [9]. The system approach is indeed more interesting, however now there are no well-defined solutions. Thus, each research group has to fill in the gaps as they see fit. Clearly, it is possible that client relay technology will be included in the upcoming amendments of IEEE 802.16 or in some other standard.

Currently, the question if client nodes should be used as relays or not is still open. There are, most likely, some cases when real channels make the cooperative transmission useless, which are typically not discussed. We believe, that in order to come up with both efficient and stable solutions, there is a need to have a tool capable of simulating cooperative network with realistic channels in context of real wireless network protocols and real-world environment. The purpose of this study is to design such tool and supply researchers with a platform for extending the understanding of cooperative networking.

Further on, we discuss the simulator in more detail. First of all, we consider the system model, main definitions and other generic issues, such as actual network under investigation and its operation principles. Further, we emphasize technical details of the implementation and operation of the simulator, compare the obtained results with those in the related works. Finally, we consider the likely research directions and plans for future development of the project.

2 System Model

In this section the system model used for simulations is discussed in detail. The scope of the model is defined, as well as some examples are given of how this scope fits into real network implementation.

2.1 Definitions and abbreviations

- Base station (BS) – a special node which is a destination for all the upstream traffic in the network. It also controls access to shared transmission medium.
- Client node (client) – a node which is a client of a network and generates own traffic.
- Conventional cooperation (CC) – a cooperation mode when the relay node always tries to assist transmission if it happens to be able to do so.
- Delay – the amount of time between packet arrival and the end of the frame when it was successfully delivered. If the packet was dropped delay is not taken into account.
- Downstream traffic – traffic that has a client node as destination. Downstream traffic is not considered in scope of this paper.
- Eavesdropping – reception of a packet, which has BS as its destination by the relay node.
- Link – a logical connection between two nodes. In context of the paper links are wireless, but still strictly node to node.
- Node – any entity in a network that is able to receive packets.
- Non-cooperative mode (NC) – nodes do not relay anything.
- Packet – an atomic transmission unit. In this work we do not consider messages, so fragmentation and aggregation are out of scope.
- Relay node (relay) – a client node capable of assisting other client nodes during transmission. We do not consider any other types of relays.
- Stability region – for fixed channel conditions and node placement it is a set of arrival rates, which results in stable network behaviour. Since the stability of a network is difficult to estimate numerically, some derived parameters are used, e.g. threshold on delay or packet loss.
- Stable network – a network where all packet delays are finite, all queues are stable, and traffic is not lost due to congestion (it may be lost, however, due to transmission errors).
- Throughput – throughput is obtained by dividing the amount of successfully delivered packets by the amount of frames simulated.
- Upstream traffic – traffic that is going from client nodes.

2.2 Assumptions

Here we detail the assumptions that are made while designing the simulator.

1. Communication system
   (a) Synchronization
   System time is divided into equal time intervals, called frames. Each node is aware of the frame boundaries.

(b) Fixed network topology

There are 2 client nodes in the network, A termed the originator and R termed the relay, and a single sink node B termed the BS (see Figure 1). The originator generates new packets with the arrival rate λ_A, and the relay generates new packets with the arrival rate λ_R. Additionally, the relay may eavesdrop on the packets from the originator and store them for the subsequent retransmission. The BS receives data packets from both the originator and the relay. The BS has no own traffic.

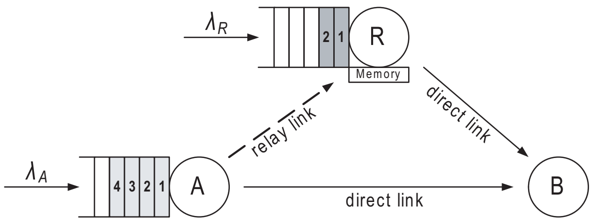

Fig. 1 Simple triangle topology

(c) Links

All client nodes are able to transmit packets to the BS. Only upstream transmissions are considered.

(d) Data packets

All data packets transmitted over the network have same length and take exactly 1 frame to be transmitted.

(e) Scheduling

All transmissions are controlled by the scheduler at the BS. Effect of scheduling discipline on the performance of the network is out of scope of the model. A round-robin scheduler is considered, which alternates the source nodes accessing the channel (see Figure 2). In particular, if the originator and the relay have pending data packets, both are granted a slot in turn. If either node is empty, the BS schedules the other node without interruptions. If both nodes have no pending packets, the system is idle. The scheduling information transmission is assumed to be over a separate channel and consumes no resources.

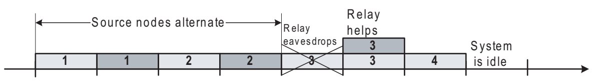

Fig. 2 Relay system example operation

2. Transmission channel

(a) Channel events

Two events are possible – success or failure to deliver a packet within a particular frame. As such, each packet is either delivered perfectly or dropped at the receiver.

(b) Imperfect channel

Packet loss probability for each link is constant and known apriori. Such model may capture the effects of fading, attenuation and interference [10]. Other models may also be used, but this is the default.

3. Feedback information

(a) Feedback signals

There are 2 PHY to MAC feedback signals – success or failure to deliver a packet.

(b) Reliability

All feedback information is error-free.

(c) Actuality

The feedback information is available by the end of the frame.

4. Clients

(a) Buffer length

Client buffer is finite, and may store up to L packets. Each relay node has a separate buffer for relay packets, its length is M packets.

(b) Incoming traffic

The numbers of packet arrivals per slot to the client queues are independent and identically-distributed (i.i.d.) random variables with means λ_A and λ_R, respectively. For simplicity, we assume Poisson arrival process.

(c) Client operation

In each frame client may receive a packet, transmit a packet or stay idle.

The above assumptions could be a reasonable approximation for the real system, if the following conditions hold

- Separate frequency channels are allocated for signalling and downstream traffic.
- Transmission power of BS is much greater than that of the client nodes.
- Packet and frame sizes are fixed and equal.

Also it should be noted that those assumptions are based on [10]. However, there are several important differences, making our model more realistic.

- In [10], the relay acknowledges the receipt of the packet from the originator and keeps transmitting the relay packet as if it was its own one. In this work the cooperation is only possible if the originator attempts retransmission of the packet. When it is scheduled to retransmit, the relay may transmit the eavesdropped packet in the same frame. This, given appropriate physical layer, greatly increases the probability of successful delivery.

- The queue lengths L and M are not infinite, but $L = 200$, because it is close to the amount of packets stored in the socket buffer and $M = 1$, since we overwrite the relay buffer every time we eavesdrop new packet.

- The scheduling system is fair. In [10] the relay node is only scheduled when originator has no packets to send.

- The originator is unaware of the cooperative help from the relay. No explicit information is transmitted between the originator and the relay by contrast to [10], where the relay was supposed to acknowledge packets received from the originator.

In the most general case the relay may choose either not to eavesdrop on the originator's packets or not to transmit them subject to some relaying policy. We leave such an opportunistic relaying out of scope of this work and restrict the relay to eavesdrop on any transmission from the originator it is able to receive and to transmit originator's packets if stored. The overall operation algorithm for the network can be summarized as Algorithm 1.

Algorithm 1 Network operation algorithm

```
repeat
  Schedule incoming traffic arrivals into client queues.
  Scheduler at base station selects node to transmit in next frame (or no nodes)
  for All client nodes in cell do
    if Relaying is allowed for node then
      if Node has same packet as the one scheduled then
        Node joins transmission
      else
        Node starts eavesdropping, trying to capture packet
      end if
    end if
  end for
  Transmit the packet and determine where it was received.
  if Packet received at the base station then
    Discard the packet from originators queue.
  end if
  if Packet received at relay node then
    Put the packet in the relay buffer, overwriting previous one.
  end if
until Network shutdown
```

2.3 Performance parameters of interest

The following system metrics are of interest:

- System throughput and per-client throughputs when relaying is allowed or not allowed.

- Mean packet delay and the delay distribution for each client in the relay and no-relay cases.

2.4 Measurement principles and simulator features

The simulation is performed using regenerative approach according to [11]. This approach allows us to obtain non-shifted averages for statistical data we collect, as well as to establish confidence intervals for measured parameters. The statistical data is collected at the regeneration points, when the network returns to its initial state. As such, we run the simulator waiting for regeneration, and for each parameter of interest we use following formulae:

$$\text{Let } X_n \text{ be a random process },$$
$$\text{and } \beta_j \text{ a regeneration point }.$$

Regeneration point is a value of n when X is in initial state. Now we define the length of regeneration cycle j as

$$a_j = \beta_{j+1} - \beta_j (j \geq 1).$$

For each cycle we define a function

$$Y_j = \sum_{i=\beta_j}^{\beta_{j+1}-1} f(X_i).$$

It may be shown that values of Y_j for all cycles are i.i.d. Now, according to [11] the mean of the measured value is

$$r \triangleq E\{|f(X)|\} = \frac{E\{Y_1\}}{E\{a_1\}}.$$

r is consistent and non-shifted estimate. And it may be shown that

$$E\{Y_1\} = E\{Y_j\} = \frac{\sum Y_j}{n},$$
$$E\{a_1\} = E\{a_j\} = \frac{\sum a_j}{n}.$$

The last 3 formulae are used in our simulator. Obtaining the confidence interval is more complex and the reader is referred to [11].

Regenerative simulation is applicable for the majority of stable networks, and our network is typically stable. If it is needed to obtain the results outside of the stability region, it is generally possible, but almost never needed. Our approach is also scalable because the regeneration does not have to happen for the entire network, but rather for a closed group of nodes. Therefore, if a node does not depend on the queue at node X, we should not consider that queue when deciding if regeneration was reached or not.

Algorithm 2 Simulating a single set of input parameters

```
repeat
  Set all queues to be empty
  time = 0
  repeat
    Schedule traffic on client nodes
    Simulate transmission
    time = time + 1
    if time > maxtime then
      Consider the system unstable and exit
    end if
  until all queues are empty
  Register the regeneration and calculate the error estimates
until Target accuracy reached or maximum amount of cycles exceeded
Save obtained data to trace file
```

Summarizing, in order to obtain the reliable results, for each point we simulate network according to Algorithm 2.

Regenerative approach also allows one to see whether network is stable or not, as well as minimize the amount of calculations involved. Since we can estimate the confidence intervals, the simulation is never run longer than needed. We introduce target accuracy as $T = error\_estimate/value \cdot 100\%$. The user may define target accuracy in terms of maximum simulation time or in terms of target accuracy. The speedup factor of the latter method depends on the actual settings, and may be up to 10 when target accuracy is about 15%.

Another performance gain was obtained by implementing the simulator in C language without any scripting involved in the simulation. C was chosen over C++ mostly due to easier optimization and better overall performance of the program. Actual speedup compared to original Matlab [12] implementation of the same algorithms is about 100000. For example, simulating a network described above with 128 steps for arrival rates at each node and target accuracy of 5% takes about 15 seconds of real calculation time. Doing the simulation with 32 steps and the same target parameters by Matlab script took a little over 4 hours on same machine. It is hard to imagine how long it would have taken to simulate a whole cell with hundreds of users.

The current design is not only efficient, but also allows to extend the amount of nodes easily, as well as to introduce more comprehensive channel models. Currently, the ITU pedestrian channel and additional traffic profiles are under development.

As an intermediate result we have a highly extensible and efficient simulation platform for assessing the cooperative networking. As a huge benefit over implementation as a plugin for NS2 [13] or other simulation platforms, we know exactly how our simulation works. Thus, we can be perfectly sure that it is actually simulating what is needed and nothing else.

2.5 Graphical and numerical results

Since the research [10] was used as the starting point for the simulator, it is interesting to compare their analytical results with our simulation data.

For this purpose we use channel model proposed in [10], which captures the effects of fading, attenuation and interference at the physical layer. The model is described by a probability matrix, defining

- $q^{(B)}_{A|A}$ – probability that packet from A is received at B when only A transmits.
- $q^{(B)}_{R|R}$ – probability that packet from R is received at B when only R transmits.
- $q^{(R)}_{A|A}$ – probability that packet from A is received at R when only A transmits.
- $q^{(B)}_{A|A,R}$ –probability that packet from A is received at B when both A and R transmit.

The actual values are obtained from [10]: $q^{(B)}_{A|A} = 0.3$, $q^{(B)}_{R|R} = 0.7$, $q^{(R)}_{A|A} = 0.4$, $q^{(B)}_{A,A|R} = 0.5$.

Below we present some plots obtained by simulating the described network. In the Figure 3 one may find the stability regions of the network obtained during simulations for cooperative and non-cooperative cases, compared to those found in [10]. Theoretical stability regions are defined by following formulae.

$$\mathfrak{R}_{NC} = \left\{ (\lambda_A, \lambda_R) : \frac{\lambda_A}{q^{(B)}_{A|A}} + \frac{\lambda_R}{q^{(B)}_{R|R}} < 1 \right\}.$$

$$\mathfrak{R}_{CC} = \left\{ (\lambda_A, \lambda_R) : \frac{(q^{(R)}_{A|A} + q^{(B)}_{R|R} - q^{(R)}_{A|A} \cdot q^{(B)}_{A|A})\lambda_A}{q^{(B)}_{R|R}(q^{(R)}_{A|A} + q^{(B)}_{A|A} - q^{(R)}_{A|A} \cdot q^{(B)}_{A|A})} + \frac{\lambda_R}{q^{(B)}_{R|R}} < 1 \right\}.$$

In Figure 4 one may find the throughput and delay gains due to cooperative transmission when relay node is free and in saturation conditions.

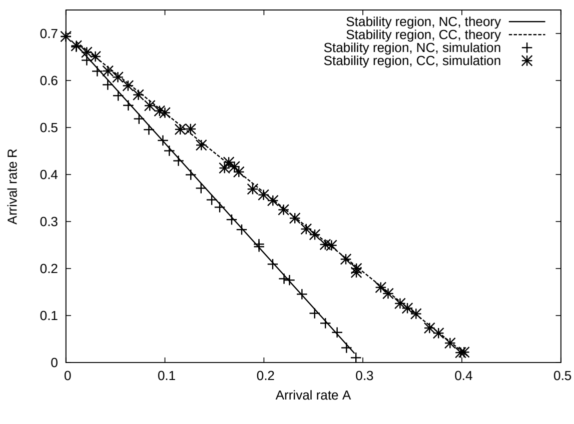

Fig. 3 Simple triangle topology – stability region

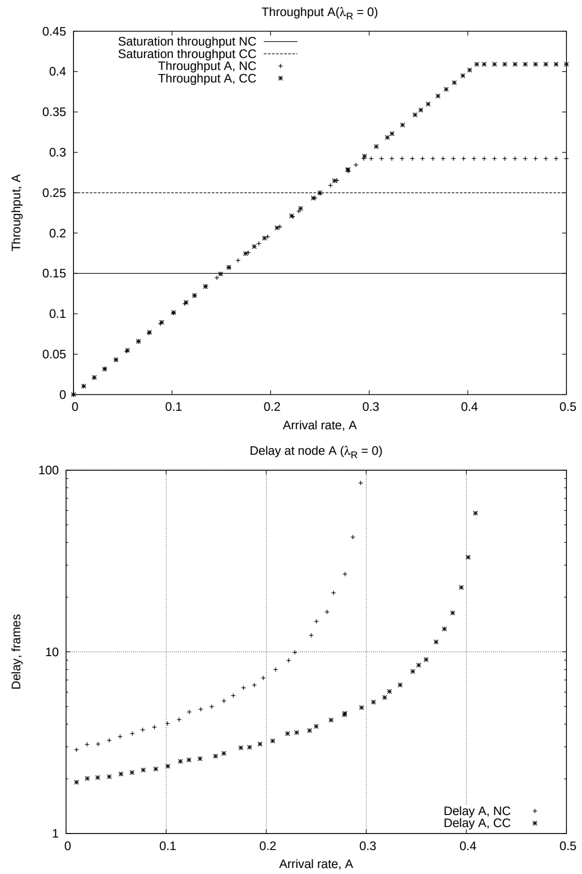

Fig. 4 Simple triangle topology – throughput and delay

It can be seen, that although the assumptions are not exactly the same, and the whole relaying scheme was changed, the numerical results still match theoretical ones quite well. It may be also noted, that just 0.2 difference in delivery probability results in the throughput gain over 25% for considered scenario. It is also clear that relaying does not decrease the throughput of the system. Clearly, such a simplified channel model might be masking some channel properties, so its use is more proof-of-concept rather than real application of the simulator. The question of how much will the gain be in the more realistic conditions is subject for the further study.

3 Future plans and perspectives

The proliferation of wireless networks introduces novel important research directions, including client cooperation, energy efficient communication, co-existence, spectrum aggregation techniques and others. These directions are insufficiently addressed by the conventional simulation methodology and existing analytical models, which cover only static or semi-static cellular environments. Moreover, known models fail to account for many realistic performance factors, such as realistic traffic arrival flows, predefined QoS parameters, wireless channel degradation factors, etc. As the result, the output of these models provides inadequate insight into the performance of a real-world wireless network. The main target of this study is, thus, the development of the advanced system level simulator (SLS) that may be used for the performance evaluation of a practical multi-cell communications system compliant to the latest IEEE 802.16m and/or LTE-Advanced specifications.

The novel SLS should be capable of evaluating the basic trade-off between the metrics of interest, including individual and system throughput, power, energy efficiency and fairness. It should also take advantage of the realistic channel models (e.g. ITU-Ped B), client placement models (e.g. IEEE 802.16m EMD [14]), practical traffic patterns (CBR, HTTP, VoIP, etc.) and power control, sophisticated scheduling algorithms. It should allow for detailed per-client and system-wide statistics collection and flexible post-processing. The SLS should have reconfigurable client behaviour and modular structure with simple extension to additional features and mechanisms. Last but not least, it should be written in well-optimized C code to reduce the burden of the extensive simulations.

The advanced SLS aimed by this study appears to be the first of its kind and indicates significant promise for the entire research area. It is expected that the novel simulator and its extensions will become of significant importance towards further development of communications technologies. It is primarily intended for, but not limited to, cellular operators, telecommunications research companies, cellular equipment vendors and mobile software companies.

Acknowledgements

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